

THE ADVANCED ACCUMULATOR

Non-Proprietary Version

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Revision History (Cont.)

Revision	Page	Description
2	3-6	<p>4. The distance between the center of vortex chamber and the center line of small flow pipe, which is in parenthesis in inches [], is fixed to the correct value [].</p> <p>5. The height of standpipe (the distance between the bottom of anti-vortex cap and the top of vortex chamber), which is in parenthesis in inches [], is fixed to the correct value [].</p>
	4.2.2-3	6. "(standpipe's diameter)" is deleted from explain of "L" reflecting the response to RAI 15 of "MHI's Response to NRC's RAI on Advanced Accumulator for US-APWR Topical Report MUAP-07001-P (R1), UAP-HF-08174-P/NP (R0)."
	4.2.4-3 (Fig.4.2.4-2)	7. The height of test tank [] mm is converted to [] inches and added.
	4.2.4-4 (Fig.4.2.4-3)	8. The distance between the center line of injection pipe and the top of vortex chamber, which is in parenthesis in inches [], is fixed to the correct value [].
	4.2.4-5 (Fig.4.2.4-4)	<p>9. The distance between the center of standpipe inner section and the center of vortex chamber of actual flow damper, which is in parenthesis in inches [], is fixed to the correct value [].</p> <p>10. The distance between the throat and diffuser end of actual flow damper, which is in parenthesis in inches [] is fixed to the correct value [].</p> <p>11. The inner diameter of outlet port of test flow damper, which is in parenthesis in inches [], is fixed to the correct value [].</p> <p>12. The radius value at the top of standpipe of test flow damper; [] mm is converted to [] inch and added.</p>

Revision History (Cont.)

Revision	Page	Description
2	5.3 Instrument Uncertainties	<p>13. The title, text, and Table 5.2-2 are corrected appropriately reflecting the response to Question 17-C in "Response to NRC's Questions for Topical Report MUAP-07001-P(R1) ADVANCED ACCUMULATOR, UAP-HF-07086-P/NP(R0)."</p> <p>And other scribal errors are corrected in whole report.</p>
3	1.0 2.4 4.3-1 through 4 7.0 REFERENCES Appendix A	<p>Description is corrected because the DCD has already been submitted.</p> <p>Equation (2-8) is corrected because of typographical error.</p> <p>Section 4.3 is revised to reflect based on the discussion with the NRC.</p> <p>7.0 REFERENCES is added</p> <p>Appendix A is added to reflect the modification of Section 4.3.</p>
4	General 4.3 Validity and Scalability of Flow Rate Characteristics 5.0 Concept of the Safety Analysis Model 7.0 References	<p>Editorial Collections and modifications for readability</p> <p>Section 4.3 and Appendix A is revised to reflect based on the discussion with the NRC.</p> <p>Chapter 5 is revised to describe the total uncertainty of the advanced accumulator used for the safety analyses.</p> <p>Reference document is revised in Chapter 7.0</p>

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List of Acronyms

ACC	Advanced Accumulator
A/D converter	Analog to Digital Converter
ANSI	American National Standards Institute
APWR	Advanced Pressurized Water Reactor
ASME	American Society of Mechanical Engineers
CD	Discharge Coefficient
CFR	Code of Federal Regulations
COL	Combined Operation License
CRT	Cathode-Ray Tube
CS/RHRS	Containment Spray / Residual Heat Removal System
ECCS	Emergency Core Cooling System
GT/G	Gas Turbine Generator
HHSI	High Head Safety Injection
LOCA	Loss-of-Coolant Accident
MHI	Mitsubishi Heavy Industries, Ltd
NQA	Quality Assurance Program Requirements for Nuclear Facilities
PCT	Peak Clad Temperature
PC	Personal Computer
PRZ	Pressurizer
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCS	Reactor Coolant System
R/V (RV)	Reactor Vessel
RWSP	Refueling Water Storage Pit
S/G	Steam Generator
SI	Safety Injection
SIP	Safety Injection Pump
USNRC	United States Nuclear Regulatory Commission

ABSTRACT

The US-APWR Advanced Accumulator (ACC) simplifies the emergency core cooling system (ECCS) design by integrating the short term large flow rate design requirements currently satisfied by conventional accumulators and the low head safety injection pumps of a conventional pressurized water reactor (PWR) into a single passive device, the ACC. Upon initiation of a loss of coolant accident (LOCA) event, all low head injection requirements are satisfied by the ACC. Following depletion of the ACC's water volume, the long-term ECCS flow requirements are met by the high head safety injection pumps thus eliminating the need for low head injection pumps. Further more, the immediate availability of low head flow provided by the ACC upon loss of electrical power provides additional time to permit activation of the emergency backup power supplies.

Characteristics of the passive ACC, the detailed design of the ACC, the scaled testing program for the ACC, and the concept of the safety analysis model are discussed in this report.

The ACC has a flow damper which primarily consists of the stand pipe and vortex chamber. When the ACC water level is above the top of the standpipe, water enters the vortex chamber through both inlets at the top of the standpipe and at the side of the vortex chamber injecting water with a large flow rate. When the water level drops below the top of the standpipe, the water enters the vortex chamber only through the side inlet and vortex formation in the vortex chamber achieves the small flow rate injection.

In the first stage of injection, the ACC provides large flow injection to refill the reactor vessel then automatically reduces the flow as the water level decreases. This small flow stage of injection in conjunction with the high head safety injection pumps provides for core reflooding, thereby eliminating the conventional low-head injection system.

In order to verify this unique design for the US-APWR, four types of scaled tests were performed: 1/8.4, 1/3.5, 1/5, and full height 1/2-scale model tests. These tests used visualization to confirm flow rate switching, vortex formation, and the prevention of gas entrainment into the vortex chamber at the end of the large flow stage of injection. The injection test provides the performance data required for quantitative evaluation of ACC flow.

Major results of the tests include:

- (1) From the results of the 1/8.4 scale test, it was confirmed that switching from large flow to small flow occurs smoothly and a stable level was maintained in the stand pipe.
- (2) From the results of the 1/3.5 scale test, it was confirmed that a sharp flow rate switching without gas entrainment was achieved.
- (3) From the results of the 1/5-scale test, it was confirmed that no vortex was observed during the large flow injection stage, and a stable vortex was formed in the vortex chamber during the small flow injection stage.
- (4) From the results of the full height 1/2-scale tests, it was confirmed that the flow characteristics of the flow damper can be represented by dimensionless numbers and are independent of the scaling. Therefore the similarity law that evaluates the actual flow damper can be applied.

The ACC design will improve the overall safety of pressurized water reactors by the innovative application of the flow damper which assures the early stage of LOCA injection flow is satisfied by a highly reliable passive system. This innovation reduces the necessity of relying on

maintenance sensitive components, such as low head safety injection pumps, for assuring LOCA injection flow. This provides sufficient relief from the need for rapid start emergency diesel generator backup power and permits use of highly reliable gas turbine generators.

The flow characteristics of the ACC have been verified by thorough testing and can be fully described as a function of dimensionless numbers. Empirical flow rate coefficients have been developed from the test results and will be used in an integrated thermal hydraulic model of the US-APWR Reactor Coolant and ECCS systems to assure the US-APWR meets or exceeds all US safety standards.

1.0 INTRODUCTION

This report describes the Mitsubishi Heavy Industries, Ltd. (MHI) Advanced Accumulator (ACC) design that will be used in MHI's Advanced Pressurized Water Reactors (APWR), and MHI's US-APWR. MHI intends to seek certification of the US-APWR design from the United States Nuclear Regulatory Commission (USNRC) and offer the design to utility companies for installation in the United States. The purpose of this document is to provide the design details and confirmatory testing results of the ACC to the USNRC in order to facilitate the review of this innovation in support of the US-APWR Design Certification Application. Review and approval of this Topical Report should increase the efficiency of the US-APWR Design Certification process and any subsequent Combined Operating Licenses (COL) which reference the US-APWR Design.

The ACC is an accumulator tank with a flow damper. The tank is partially filled with borated water and pressurized with nitrogen. It is attached to the primary system with a series of check valves and an isolation valve and is aligned during operation to allow flow into the primary coolant system if the primary system pressure drops below the pressure of the accumulator. The ACC design combines the known advantages and extensive operating experience of a conventional accumulator used for loss of coolant accident (LOCA) mitigation in pressurized water reactors with the inherent reliability of a passive fluidic device to achieve a desired reactor coolant injection flow profile without the need for any moving parts.

Incorporation of the ACC into the US-APWR design and LOCA mitigation strategy simplifies a critically important safety system by integrating an inherently reliable passive safety component into an otherwise conventional Emergency Core Cooling System (ECCS). This design improvement will allow the elimination of the low head safety injection pumps, and increases the amount of time available for the installed backup emergency power system to actuate. It is expected that the use of ACCs rather than low head safety injection pumps in the US-APWR design will reduce the net maintenance and testing workload while maintaining a very high level of safety.

This Topical Report describes the principles of operation, the important design features, and the extensive analysis and confirmatory testing program conducted to assure the performance of the ACC is well understood.

2.0 CHARACTERISTICS OF THE ADVANCED ACCUMULATOR (ACC)

2.1 ECCS Performance During a LOCA

Emergency core cooling during a Loss-of-Coolant Accident (LOCA) is one of the primary functions of the ECCS. During a large break LOCA, the fuel cladding temperature increases due to the significant loss of reactor coolant from the primary system. The ECCS is required to inject water into the core to limit the rise of fuel temperature as follows:

Step 1: Inject water at a high flow rate to rapidly refill the lower plenum and downcomer of the reactor vessel. (Core Refilling)

Step 2: Recover the core water level using the water head in the downcomer. Large ACC flow to the core keeps the water level in the downcomer high and quickly re-floods the core. (Core Reflooding)

Step 3: After core reflooding is completed, water injection is continued in order to remove decay heat and maintain the core flooded. (Long-Term Cooling)

The performance requirements for the ECCS in a conventional nuclear plant during a large break LOCA is fulfilled using the following subsystems.

Step 1: Accumulator System

Step 2: Low Head Injection System and High Head Injection System

Step 3: Low Head Injection System and High Head Injection System

Thus, in a conventional nuclear plant, the functions of the ECCS during a LOCA are assigned to three subsystems: the Accumulator System, the Low Head Injection System and the High Head Injection System.

In the US-APWR, the ACC, which automatically shifts its flow rate from large to small, is incorporated into the safety system design. The function of the Low Head Injection System is accomplished by the Accumulator System and the High Head Injection System, therefore, the Low Head Injection System can be eliminated to simplify the configuration of the ECCS.

The performance requirements are fulfilled by the US-APWR ECCS subsystems during a large break LOCA as described below and as shown in Fig. 2.1-1.

Step 1: Accumulator System

Step 2: Accumulator System and High Head Injection System

Step 3: High Head Injection System

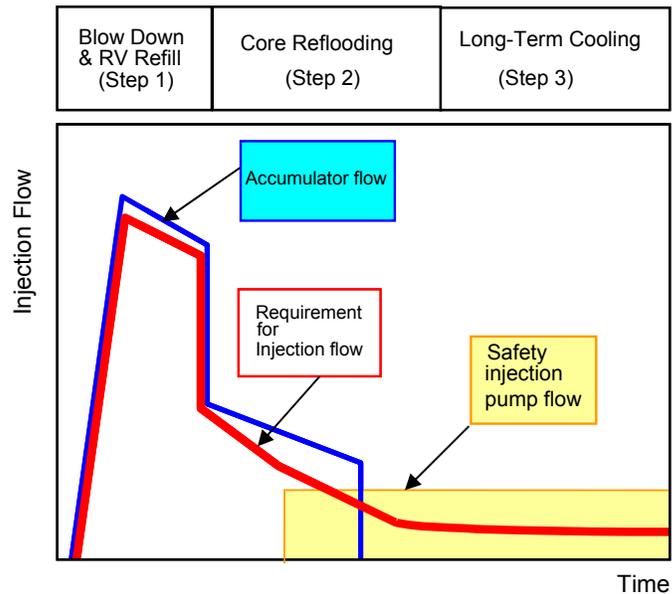


Fig. 2.1-1 ECCS Performance During a Large LOCA

During a large break LOCA, it is necessary to start the safety injection pumps prior to the end of accumulator injection to continuously inject water to the core. The ACC injects water longer than a conventional accumulator, thereby allowing more time for the safety injection pumps to start. This additional time margin allows the US-APWR to use gas turbine generators for the emergency power source, if needed.

The system configuration of the US-APWR ECCS is shown in Fig. 2.1-2. Four accumulators are installed and each ACC is connected to a Reactor Coolant System (RCS) cold leg. Four High Head Injection Subsystems are installed and inject directly into the vessel downcomer following accumulator injection. Low Head Injection subsystems are not installed.

A more detailed description of the ACC will be provided later.

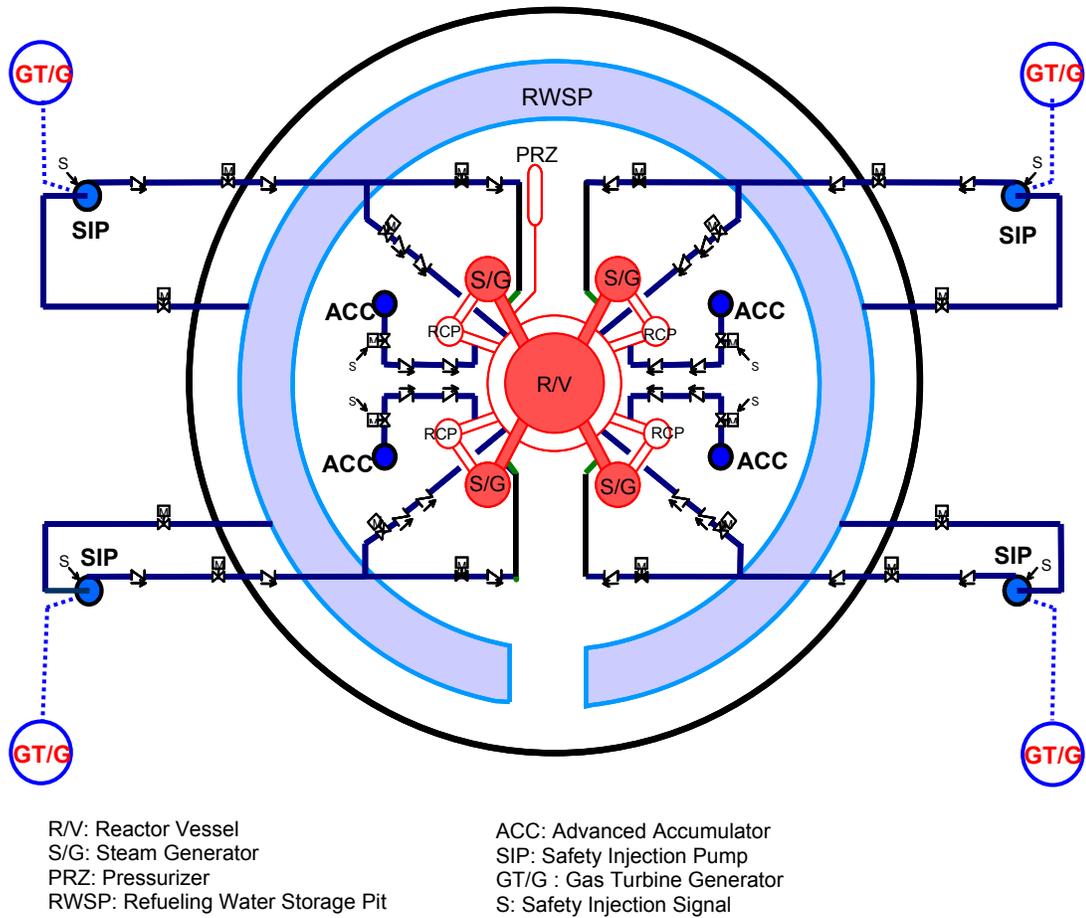


Fig. 2.1-2 System Configuration of the US-APWR ECCS

2.2 Principles of ACC Operation

2.2.1 Concept and Principle of Flow Switching

The ACC is a water storage tank containing a flow damper that automatically switches the flow rate of cooling water injected into the reactor vessel from a large to a small flow rate.

The conceptual drawing of the ACC is shown in Fig. 2.2.1-1.

The ACC is a simple device with no moving parts. The ACC is a large tank containing a flow damper. In essence, the "flow damper" consists of the standpipe, the large flow pipe, the small flow pipe, the vortex chamber, and their connections. The outlet part of the flow damper is connected to the injection pipe. There is a vortex chamber with its outlet connected to the injection piping exiting the accumulator. The small flow pipe is tangentially attached to the vortex chamber. The large flow pipe connects the bottom of the standpipe radially to the vortex chamber. The height of the standpipe inlet port is located at a tank level that corresponds to the interface between the volume of water needed for large flow rate injection and the volume needed for small flow rate injection.

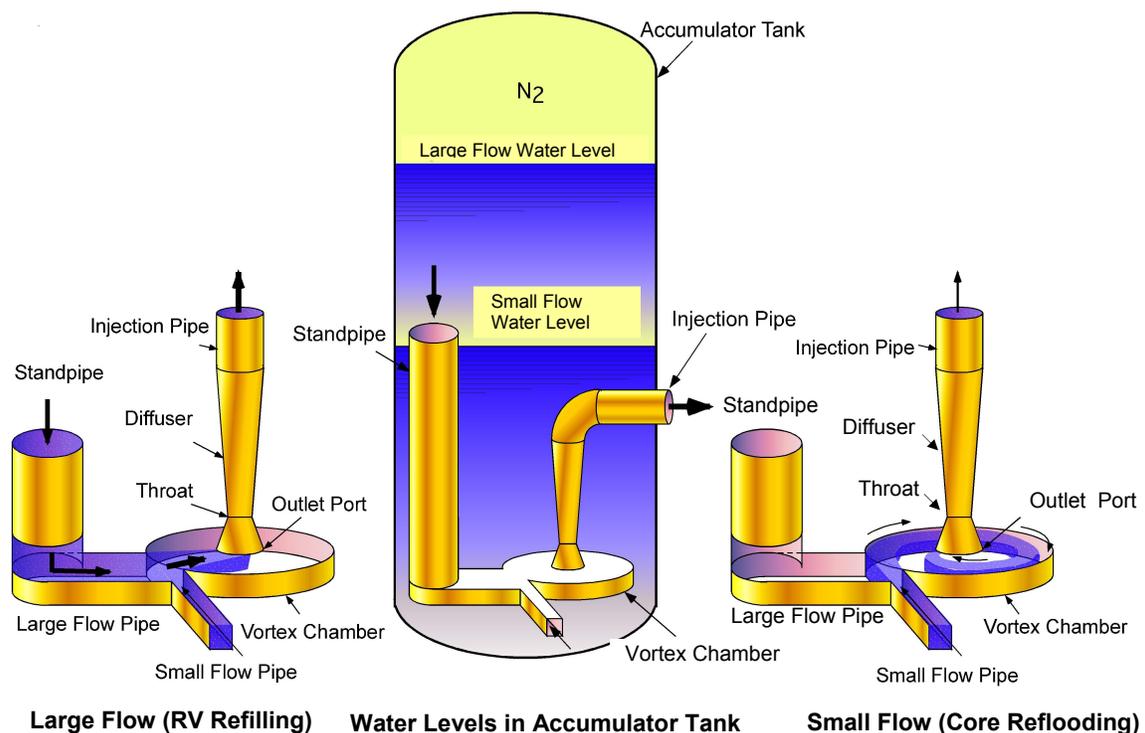


Fig. 2.2.1-1 Principle of Advanced Accumulator Operation

When a Loss of Coolant Accident (LOCA) occurs and pressure in the reactor vessel decreases, the check valves in the injection pipe open to permit injection of ACC water into the reactor vessel. Since the water level in the accumulator is initially higher than the elevation of the inlet of the standpipe, water flows through both the large and small flow rate pipes. These flows collide with each other so that no vortex is formed in the vortex chamber. The angle of collision, θ , is determined so that the flow from the large flow rate pipe cancels out the angular momentum of the flow from the small flow rate pipe. Consequently, the overall flow resistance of the flow damper is small resulting in a large flow. Fig. 2.2.1-2 shows additional details of the flow damper.

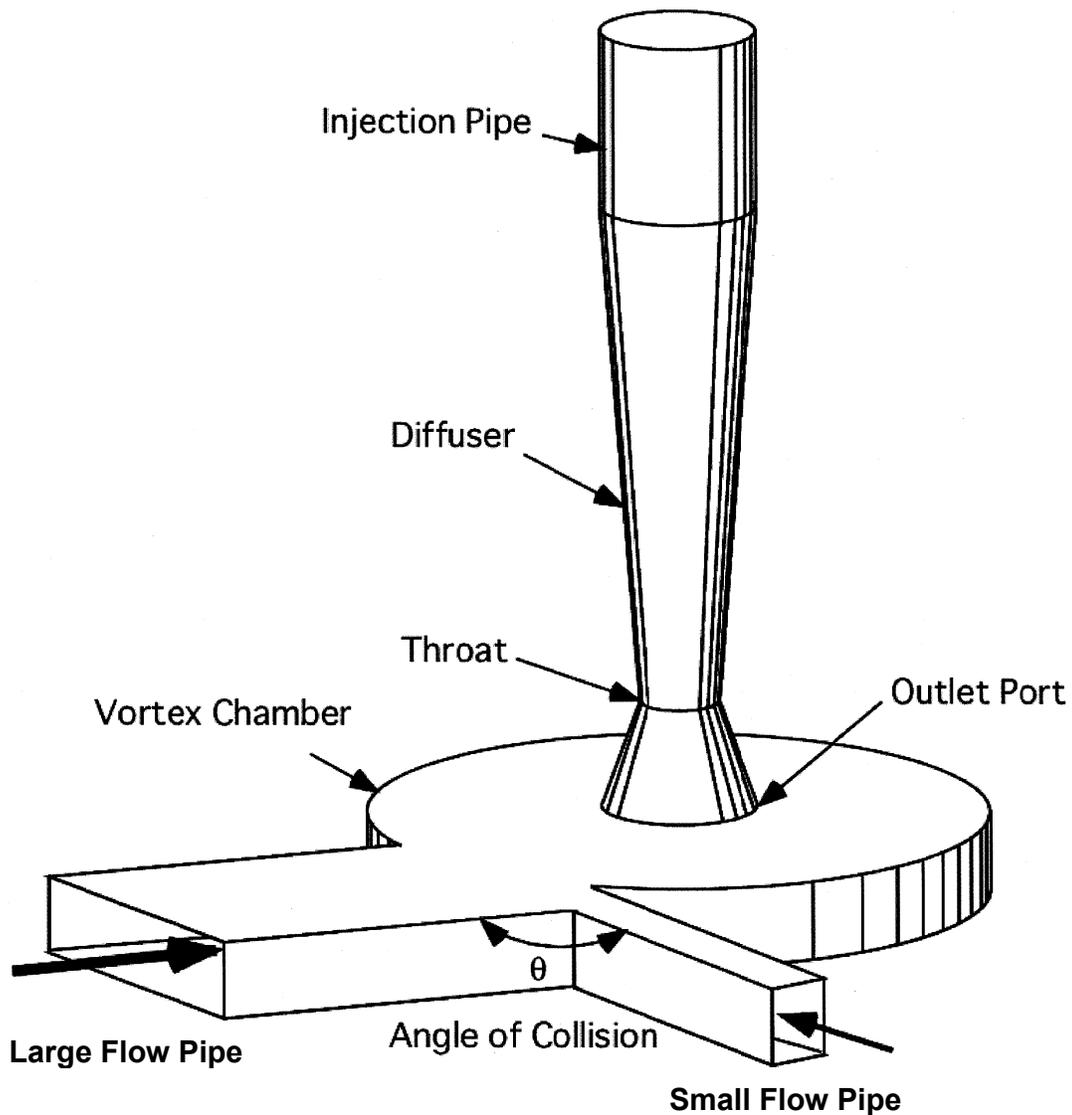


Fig. 2.2.1-2 Flow Damper

High flow continues until the water level in the accumulator comes down to the inlet level of the standpipe, and the flow into the standpipe stops. The flow in the large flow rate pipe comes to a near-stop and without this flow from the large flow pipe, the flow from the small flow rate pipe forms a strong vortex in the vortex chamber. As a result of centripetal force, a large pressure drop (and the equivalent of a high flow resistance) occurs along the radius of the vortex chamber between the small flow pipe and the outlet port. Therefore, a small flow rate is achieved with a vortex rather than with moving parts.

The strength of the vortex in the chamber depends on the ratio of the diameter of the vortex chamber, D , and that of the outlet port, d . The ACC design objective was to make the ratio, D/d , as large as possible. The diameter of the vortex chamber, D , is determined by the accumulator diameter, while that of the outlet port, d , is limited by the required flow rate at large flow rate conditions. In order to satisfy these design requirements and achieve a larger ratio of large to small flow rates, a throat followed by a diffuser is employed at the outlet port of the vortex chamber.

2.2.2 Expected Phenomena

1) During Large Flow Rate Stage

Since there is no vortex in the vortex chamber at large flow rates, the resistance of the flow damper is similar to that of a conventional pipe. The form resistance (that is, the resistance resulting from the piping geometry) is larger than the flow friction in the flow damper because the flow is required to make high velocity direction changes within a short distance. Therefore, the pressure loss of the flow damper will be primarily due to form resistance and secondarily due to flow friction. The latter can be evaluated by its Reynolds number. The form resistance is independent of Reynolds number.

The diffuser recovers pressure after the throat in order to reduce the losses, and the pressure at the throat is lower than that in the injection pipe at large flow rates. If the pressure at the throat drops below the critical pressure of cavitation inception, cavitation may occur. If cavitation occurs at the throat of the outlet port, the existence of bubbles may reduce the flow rate. Hence, the cavitation factor will be the main parameter affecting the flow rate coefficient if the effect of friction is neglected.

The pressure in the accumulator is over 580 psig (4 MPa [gage]) at the beginning of injection and comes down to about 145 psig (1 MPa [gage]) at the end of large flow rate injection stage. Dissolved nitrogen gas in the stored water will separate out due to the pressure drop and may affect the flow rate. However, the effects of the dissolved nitrogen were simulated in full height and full pressure experiments to verify that dissolved gases will not significantly affect the ACC flow rate. The details of the test will be provided later in this report.

Additional details for the flow phenomena are provided in Section 4.3.

2) During Flow Rate Switching

At the end of the large flow rate injection stage, water stops flowing into the standpipe. A water surface is formed within the standpipe and the water column in the standpipe still has momentum at that time. The inertia of the water column makes the water surface undershoot below the ACC water level that balances with the pressure difference inside and outside of the standpipe. The water level recovers to its balanced level thereafter. Fig. 2.2.1-3 shows a schematic chart of the water level transient in the standpipe. The standpipe must be designed to ensure that nitrogen gas in the tank does not flow into the injection pipe during undershoot. This effect was evaluated in the testing described later in this report.

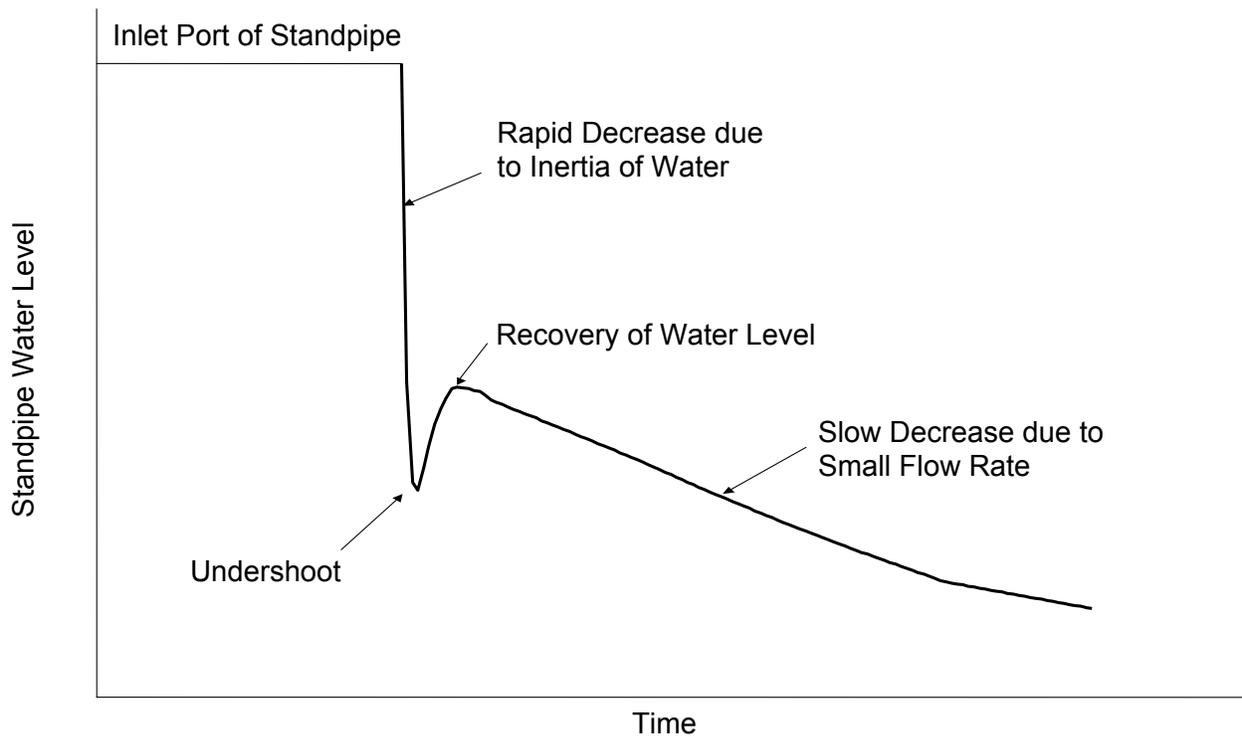


Fig. 2.2.1-3 Example of Water Level Transient in Standpipe (Schematic Chart)

3) During Small Flow Rate Stage

After flow in the standpipe is almost stopped, a strong and steady vortex flow is formed in the vortex chamber by flow from the small flow pipe. Since the pressure loss in the small flow rate pipe is negligible, the static pressure at the exit of the small flow rate pipe equals the static pressure in the accumulator minus the dynamic pressure in the small flow rate pipe. In other words, the difference between the water level in the tank and in the standpipe is equal to the dynamic pressure in the small flow rate pipe, which is much smaller than the pressure drop due to a vortex in the chamber. This is the main feature of the flow damper that prevents gas leakage during the small flow rate stage.

Pressure drop through the flow damper is due to the development of strong vortex at small flow rates. Pressure recovery in the diffuser after the throat is negligible during small flow rate, and most of the dynamic pressure developed in the vortex is lost in the diffuser. The scaled test results indicate that the flow performance is independent of any potential cavitation at the center of the vortex.

If the influence of friction is negligible, the flow rate coefficients will be similar for any size of flow damper.

Additional details for the flow phenomena are provided in Section 4.3.

2.3 Performance Requirements for the ACC

The functions of the ACC during a large break LOCA, as described in Section 2.1, are refilling the lower plenum and downcomer immediately following the reactor coolant blow down (Step 1), and establishing the core reflooding condition by maintaining the downcomer water level after refilling the core (Step 2). In this section, these functional requirements are quantified as performance requirements and design requirements.

2.3.1 Performance Requirements for Large Flow Injection

The lower plenum and downcomer of the reactor vessel shall be filled by large flow injection. Since the time required for accomplishing large flow injection is the dominant factor for the Peak Clad Temperature (PCT), the performance requirement is that the lower plenum and the downcomer are filled with water as rapidly as possible during the refilling period.

2.3.2 Performance Requirements for Small Flow Injection

1) Basic concept

It is important to keep the downcomer filled with ECCS water, in order to ensure that a water-head is maintained to force ECCS water flow into the core through the lower plenum of the reactor vessel to provide core cooling (See Fig. 2.3.2-1).

2) Required injection flow rate

The required injection flow rate during the core re-flood period is determined as follows.

The required flow rate is obtained from the core reflooding flow rate calculated by the hypothetical LOCA analysis, which assumes that the downcomer is filled with sufficient water to adequately achieve safety injection flow. The conventional 4-loop plant approach of a double-ended cold leg break (with a discharge coefficient of 0.6) causing the worst-case PCT is assumed for the analysis.

The required flow rate is obtained as the sum of the injection flow rate and the product of flow area times the reflooding rate for each of the following three regions (See Fig. 2.3.2-1).

- (1) Core region
- (2) Neutron reflector cooling-holes region
- (3) Neutron reflector back side region

The required injection flow rate obtained by this analysis is shown in Fig. 2.3.2-2. According to the progression of core reflooding, the difference of water-head between the downcomer and the core is reduced gradually, and the required injection flow rate also decreases gradually.

This analysis was performed using the Appendix K ECCS model with the Japanese decay heat model. Since the decay heat level of the Japanese model is lower than that of the

Appendix K model, the core reflooding rate is larger. Therefore, the Japanese decay heat model was used to obtain the conservative (larger) reflooding rate requirement.

The adequacy of the required injection flow rate will ultimately be confirmed by the ECCS performance analysis using the WCOBRA/TRAC code with ASTRUM methodology.

3) Required injection flow rate margin

The required flow rate for the small flow injection stage will be supplied solely by the ACC as described in Fig. 2.1-1 (Section 2.1). The Safety Injection pumps will provide additional ECCS flow rate margin.

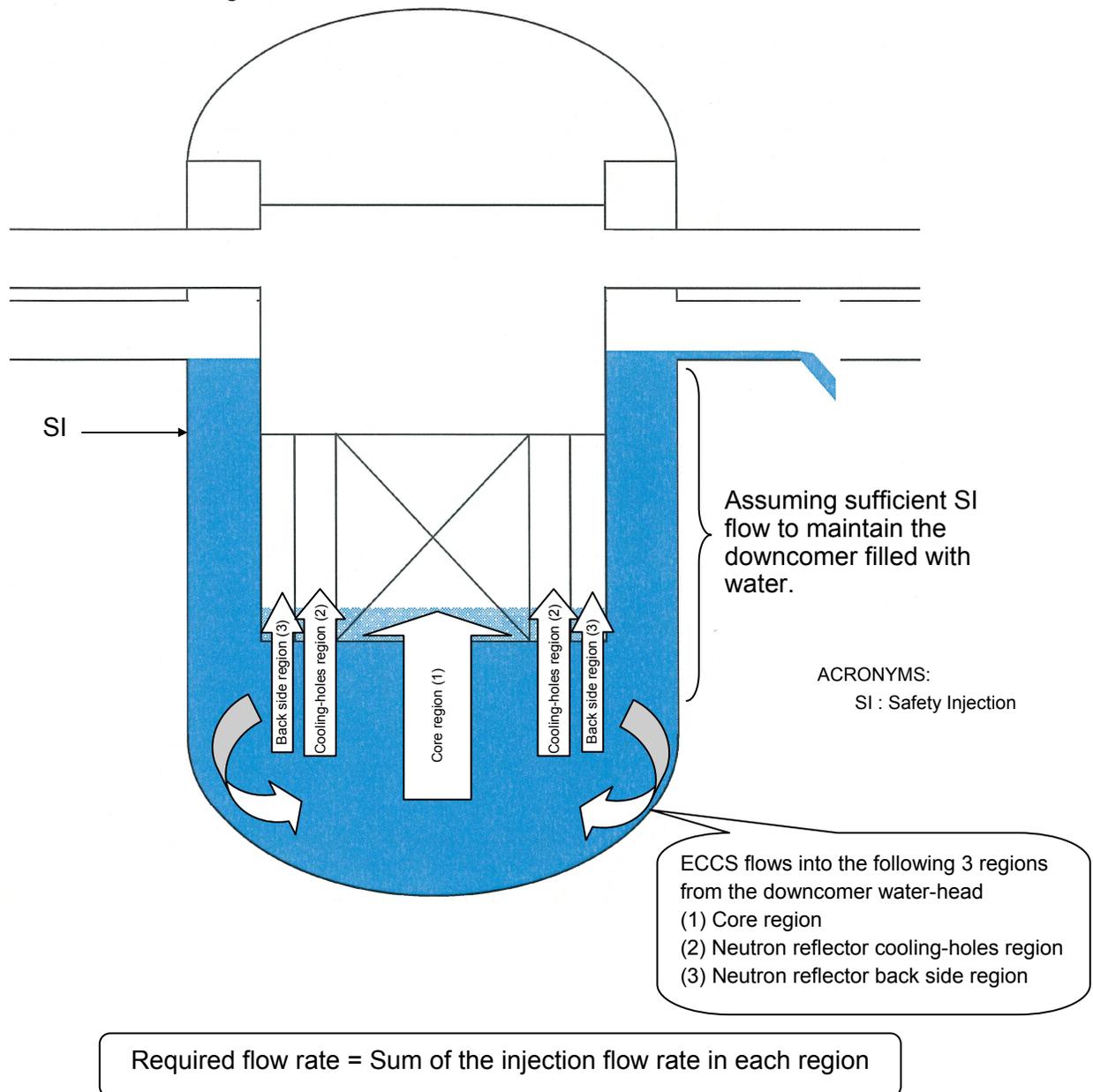


Fig. 2.3.2-1 Basic Concept for Calculation of the Required ECCS Injection Flow Rate (Core reflooding phase)



Note: According to progression of core reflooding, the difference of water-head between the downcomer and the core is gradually reduced. The required flow rate also decreases gradually.

Fig. 2.3.2-2 Required ECCS Injection Flow Rate

2.3.3 Expected ECCS Function for Various Break Sizes

In general, high PCT is postulated to occur in two break-size ranges. One is for a large-break LOCA and the other is for a small-break LOCA.

Fig. 2.3.3-1 shows the RCS pressure transient and ECCS flow injections for various break sizes.

- **Large-break size:**

Because of large break flow, the core would be uncovered and fuel-cladding temperature would rise. The ECCS injection capability requires core water level to be recovered quickly. Therefore, the prompt injection during the refill period is required to be performed by the large flow rate stage of the accumulators. (See Fig. 2.3.3-1(a))

When the accumulators inject water for medium break sizes (that is, less severe large break LOCAs) the fuel-cladding temperature does not reach high values because of the lower decay heat level at the time of ACC injection and relatively quick core reflooding due to the slow accident transition compared to larger break-sizes. (See Fig. 2.3.3-1(b))

- **Small-break size:**

Because of the loop seal and boil-off phenomena, the core would be uncovered and the fuel-cladding temperature would rise. In this case, the accumulators do not inject water for the core reflooding. The required ECCS function is the injection capability to supply the evaporated coolant in the long-term after core reflooding. Therefore, the high head safety injection pumps provide this function. (See Fig. 2.3.3-1(c))

The ECCS design will be validated by the ECCS performance evaluation analysis.

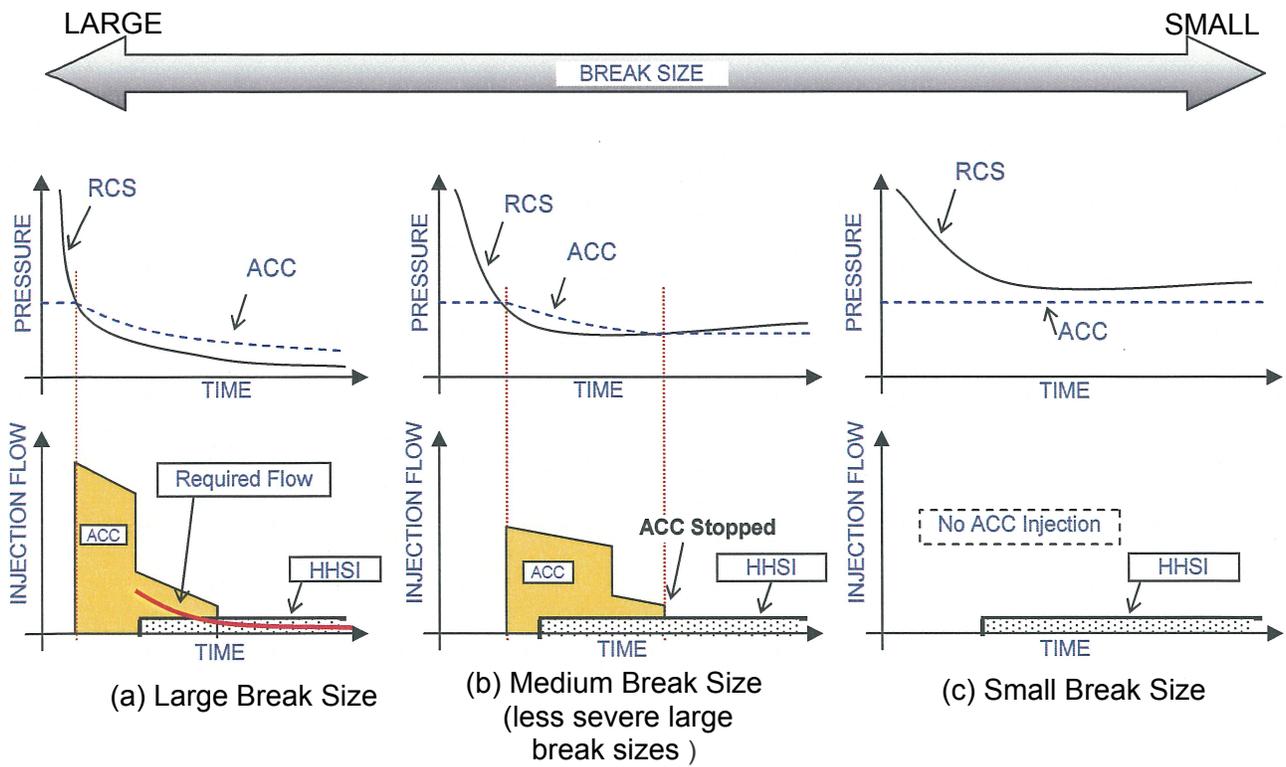


Fig. 2.3.3-1 RCS Pressure Transients and ECCS Injection Flow for Various Break Sizes

where

P_{gas}	: Accumulator gas pressure
P_{gas0}	: Initial accumulator gas pressure
V_{gas}	: Accumulator gas volume
V_{gas0}	: Initial accumulator gas volume
P_{inj}	: Pressure at the injection point
K	: Overall resistance coefficient of accumulator injection system during large flow
H_t	: Water level elevation of accumulator
H_p	: Elevation of the injection point
U	: Velocity in the injection pipe
A	: Cross section inside of the injection pipe
ρ	: Density of water
g	: Gravitational acceleration constant
t	: Time
κ	: Adiabatic exponent

Each parameter is shown in Fig. 2.3.4-3 which provides an overall view of the Advanced Accumulator System.

The PCT results were confirmed to be below [] in the APWR design stage by using these parameters for large flow injection (assuming the resistance coefficient of the accumulator injection system is []). Since the resistance coefficient of the planned accumulator injection piping and valves (K_p) is approximately [], the resistance coefficient of the flow damper during large flow (K_D) was determined to be [] using the following design requirement:

$$\begin{aligned} K_D &= K - K_p \\ &= [] \\ &= [] \end{aligned} \quad (2-4)$$

The resistance coefficient of the flow damper during large flow changes is based on the cavitation factor as described in Section 2.2. The design requirement above is specified as a target for the resistance coefficient of the flow damper at the end of RCS depressurization ([] seconds after initiation of accumulator injection), which is where the cavitation factor becomes smallest.

2) Design Requirements for Small Flow Injection

The performance requirements for small flow injection during large break LOCA are described in Section 2.3.2. The required small injection flow rate following the flow transition is [] as shown in Fig. 2.3.2-2. Assuming 3 of the 4 accumulators are available, the required flow rate is [] per tank. The expected flow rate at the end of large flow injection from each accumulator is [], as shown in Fig. 2.3.4-2. The flow-shifting ratio from large flow to small flow necessary to meet the performance requirement is as follows:

$$\begin{aligned} R &= [] \\ &= [] \end{aligned} \quad (2-5)$$

Therefore, the flow-shifting ratio of [], which is within the required flow-shifting ratio [] from large flow to small flow, is specified as a design requirement.



Fig. 2.3.4-1 RCS Pressure Transient during Large Break LOCA



Fig. 2.3.4-2 Large Flow Injection Transient during Large Break LOCA



Fig. 2.3.4-3 Overall View of the Accumulator System

Note
Refer to Section 3.1

2.4 Expected Performance of the ACC

The major design parameters for the ACC, specified to meet the performance requirements in Section 2.3.4, are as follows:

- Large flow injection water volume: []
- Initial gas volume: []
- Initial gas pressure: []
- Injection pipe inner diameter: []
- Resistance coefficient of the accumulator injection line in large flow injection: []
- Resistance coefficient of the flow damper in large flow injection: []
- Flow-shifting ratio: []

The expected injection flow characteristics based on the parameters listed above are shown in Fig. 2.4-1.

The calculation method used for this calculation is the same as described in Section 2.3.4. However, the resistance coefficient of the flow damper (K_D) is changed from [] to [] at the point where the water volume for large flow injection becomes zero. The rationale for the K_D value of [] in the small flow injection stage is shown as follows:

$$R = \frac{Q_L}{Q_S} \quad (2-6)$$

$$\frac{K_{DL} + Kp}{K_{DS} + Kp} = \left(\frac{Q_S}{Q_L} \right)^2 = R^{-2} \quad (2-7)$$

$$K_{DS} = \frac{K_{DL} + Kp}{R^{-2}} - Kp$$

$$= \left[\quad \right] \quad (2-8)$$

where

- R : Flow-shifting ratio
- Q_L : Large injection flow rate
- Q_S : Small injection flow rate
- K_{DL} : Resistance coefficient of flow damper during large flow injection
- K_{DS} : Resistance coefficient of flow damper during small flow injection
- Kp : Resistance coefficient of injection pipe



Fig. 2.4-1 Expected Performance of the ACC

3.0 DETAILED DESIGN OF THE AS-INSTALLED ACC

3.1 ACC Design Basis and Specifications

The performance and the design requirements for the Advanced Accumulator (ACC) were described in Section 2.3. This section describes the design basis and specifications of the ACC.

Each ACC connects to a corresponding RCS cold leg (4 accumulators in all) and has the function of injecting water into the core during the reactor vessel (RV) refilling process and also injecting water at a lower flow rate during the core reflooding process.

The goals of the above stated functions are as follows:

- **Refilling process (large flow injection):**

Rapidly inject 2,613 ft³(74 m³) ^{Note1} of water (equivalent to the volume of the downcomer and lower plenum of the RV) to initiate reflooding.

- **Reflooding process (small flow injection):**

Continue injecting water for approximately 180 seconds ^{Note2} following the refilling process to maintain downcomer water level through core quench.

Note1: The planned volume of the downcomer and lower plenum of US-APWR is approximately 2,295 ft³(65 m³). The required value (2,613 ft³(74 m³)) is selected to provide additional margin.

Note2: It is assumed that the duration of small flow injection from the accumulator is 180 seconds followed by the injection from the Safety Injection (SI) pumps. The duration of small flow injection is related to with the SI pump capacity. If the duration of small flow injection is short then a correspondingly larger volumetric flow rate is required from the SI pumps.

Since the water from an ACC installed on the broken loop is assumed to spill into the containment and does not contribute to core injection, only the water injected from the remaining three accumulators is available for core injection. Thus, the required volume of ACC is specified as follows:

- **Refilling process (large flow injection)**

$$2,613 \text{ ft}^{3(a)} / (2/3)^{(b)} / 3^{(c)} = 1,307 \text{ ft}^3/\text{ACC} \quad (3-1)$$

The volume of an ACC is specified to be 1,342 ft³(38 m³), which is the required 1,307 ft³ (37 m³) plus margin.

(a) Total volume of the downcomer and the lower plenum (ft³)

(b) Assumption based on the experience that 1/3 of injection flow is spilled from the broken loop to the containment

(c) Number of ACCs assumed to inject into the core

- **Reflooding process (small flow injection)**

The relationship between the amount of small injection flow and the duration of small flow injection with regard to the expected performance of the ACC defined in Section 2.4 is shown in Fig. 3.1-1. The expected duration of the small flow injection from the ACC is 180 seconds. Therefore, 724 ft³(20.5 m³) of injection water is required per ACC. Thus, 784 ft³ (22.2 m³) of injection water volume is specified giving a margin above approximately 8%. Considering the total water volume, 2,126 ft³(60.2 m³), and adding the volume of gas space and dead water volume, the required volume of a single ACC is 3,180 ft³(90 m³). The validity of this volume will be confirmed in the ECCS performance analysis. Specifications for the ACC are summarized in Table 3.1-1.

Table 3.1-1 Specifications for the ACC

Type:	Vertical cylindrical
Number:	4
Volume:	3,180 ft ³ (90 m ³)
Maximum design pressure:	700 psig(4.83 MPa [gage])
Maximum design temperature:	300 deg F (149 deg C)
Large flow injection volume:	1,342 ft ³ (38 m ³)
Small flow injection volume:	784 ft ³ (22.2 m ³)

Fig. 3.1-1 Basis of the Small Flow Injection Water Volume

3.2 ACC Dimensions and Structure

An outline drawing of the ACC is shown in Fig. 3.2-1. The inner diameter of the tank is [] ft [] and total height is []. The tank inner structure includes the flow damper and the standpipe. Because the outlet piping is above the flow damper, the unavailable “dead” water is less than that for an ACC design that has its outlet piping attached under the flow damper due to the need for increased installation space. The ACC main dimensions are shown in Fig. 3.2-1.

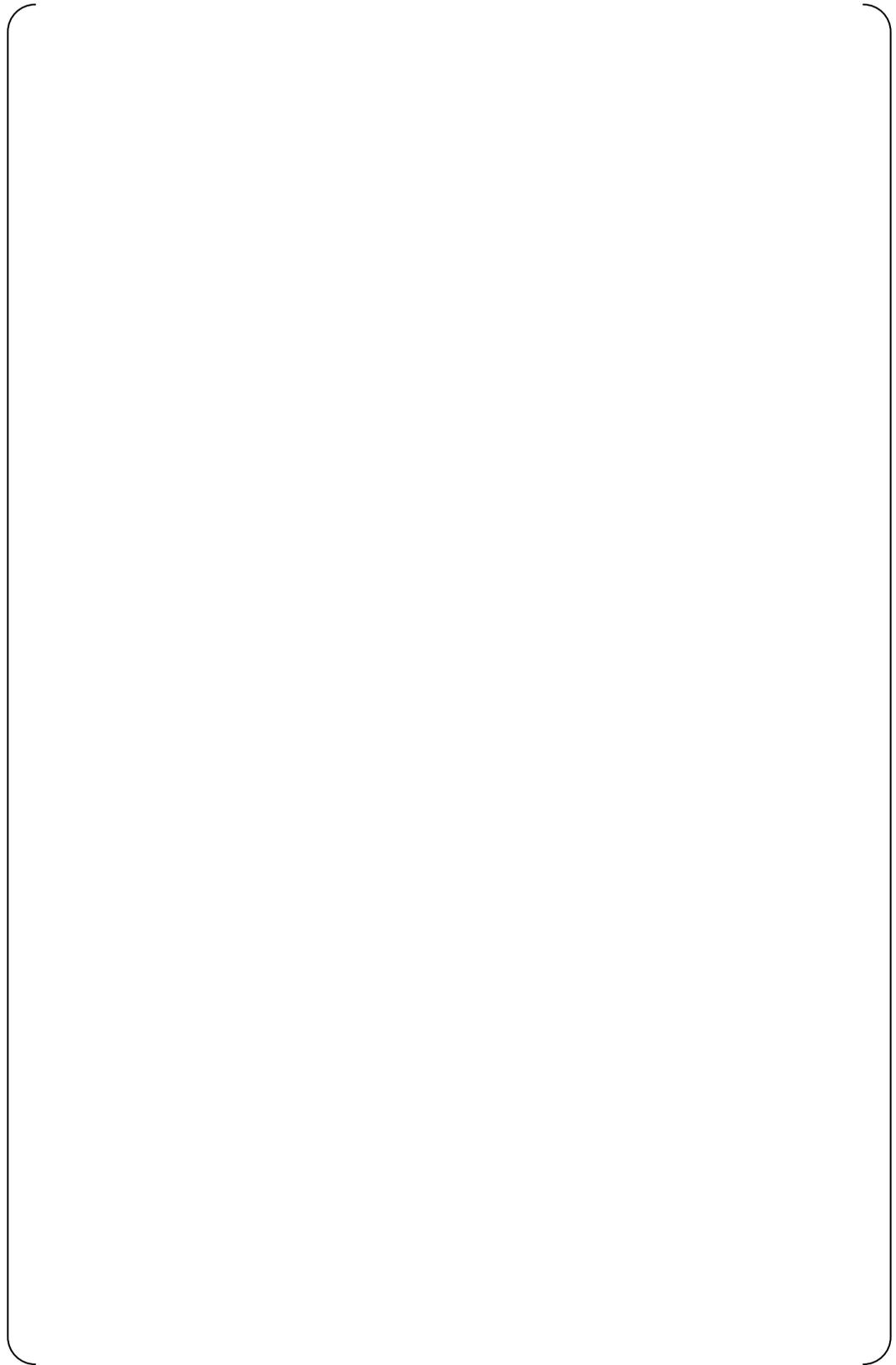


Fig. 3.2-1 Outline Drawing of Advanced Accumulator

3.3 Structure of the Flow Damper

The structure of the flow damper is shown in Fig. 3.3-1 and Fig. 3.3-2. The flow damper consists of an anti-vortex cap, standpipe, vortex chamber, small flow pipe, and outlet pipe. The inlet of the standpipe is set at the water level at which the flow rate switches from large flow to small flow. The anti-vortex cap installed on the standpipe inlet prevents gas entrainment just before the flow switching and improves the flow-switching characteristics. The small flow piping is connected to the vortex chamber tangentially. An anti-vortex plate is also provided at the inlet of the small flow pipe and prevents the gas in the ACC gas space from being sucked into the standpipe when the water level is reduced to the small flow inlet. During large flow injection, the flow from the standpipe and the small flow pipe collide in the vortex chamber and the resulting water stream flows out of the chamber directly without forming a vortex. The throat portion and diffuser are provided on the outlet pipe to increase the flow resistance during small flow, recover the pressure during large flow, provide a smooth transition for the pipe. The detailed dimensions, such as the inner diameters of the throat, and the vortex chamber, are determined from the tests using the ratio of Zobel diode. The basis for determining the dimensions is shown in Table 3.3-1.

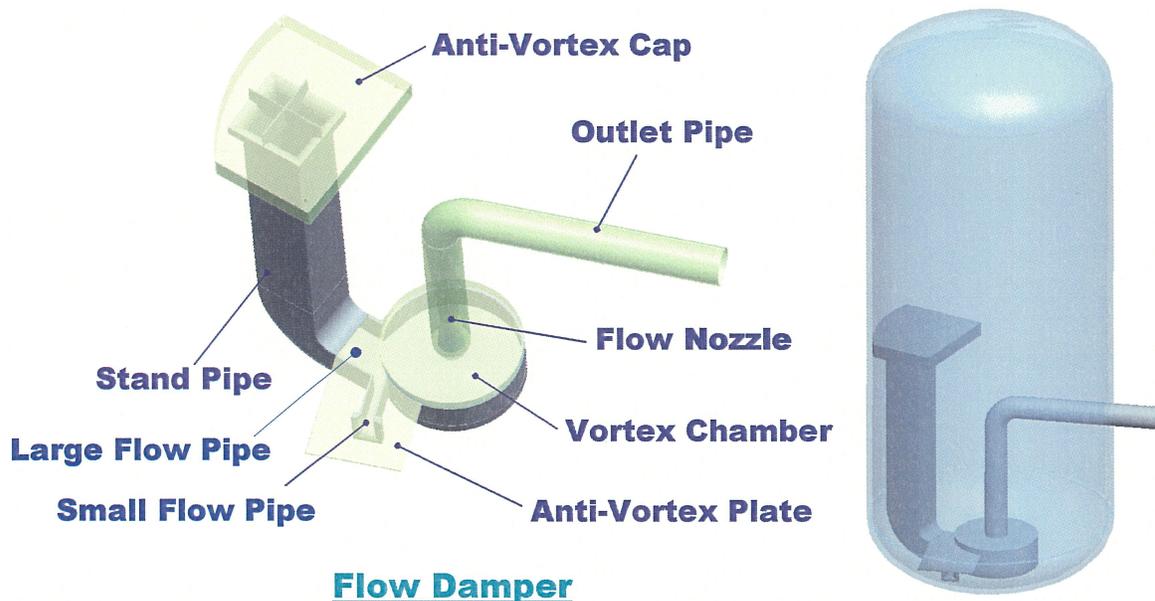


Fig. 3.3-1 Overview of the Flow Damper

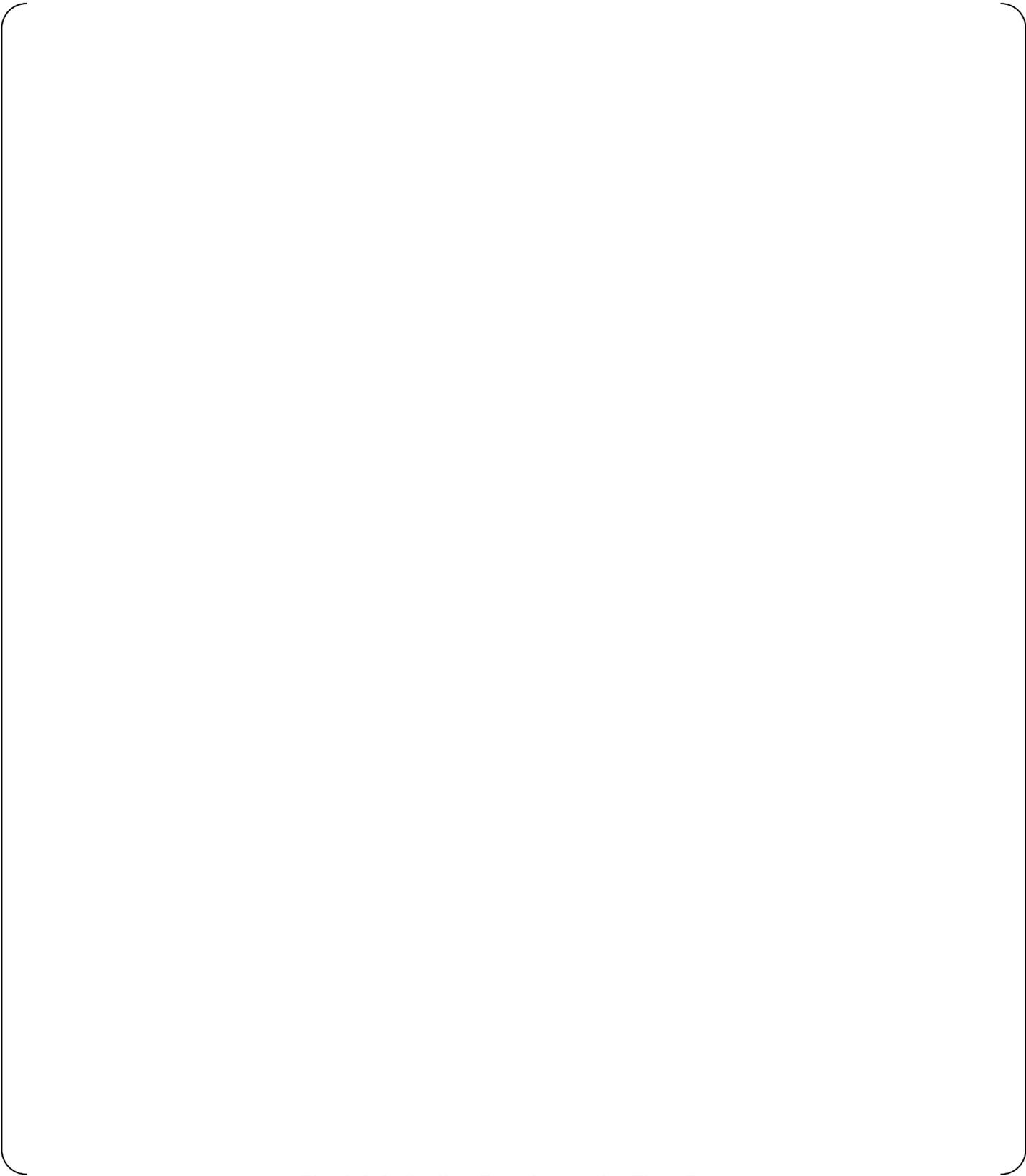


Fig. 3.3-2 Outline Drawing of the Flow Damper

Table 3.3-1 The Basis for the Flow Damper Dimension

Regions	The bases of dimension
(1) Standpipe height	Specified to assure the required injection water volume during small flow injection is maintained between the inlet of the standpipe and the upper end of the vortex chamber, and to prevent the water level from reducing below the upper end of the vortex chamber.
(2) Height of standpipe inner section	Specified to be consistent with the width of the large flow pipe connecting to the vortex chamber to assure the smooth flow from the standpipe to the vortex chamber.
(3) Width of standpipe inner section	Specified to limit the flow velocity just before the flow switching to prevent entrainment of gas during the water level transient in the standpipe.
(4) Inner diameter of the throat	The inner diameter of the throat is the dominant factor of the resistance of the flow damper during large flow. The inner diameter of the throat is specified to meet the required resistance of large flow.
(5) Inner diameter of the vortex chamber	The inner diameter of the vortex chamber is determined by tests using the ratio of Zobel diode.
(6) Height of the vortex chamber	The inner height of the vortex chamber is determined by tests using the ratio of Zobel diode.
(7) Width of small flow pipe	It is preferable that the width of the small flow pipe be as small as possible to enlarge the flow damper resistance during small flow. However, if the aspect ratio of the small flow pipe (height/width) is large, a stable jet flow is not formed. It is necessary that a stable jet flow is induced from the small flow pipe to the vortex chamber in order to form the stable vortex. Thus, the width of the small flow inlet pipe is specified with an aspect ratio of [] ^{Note} . Note: Max. aspect ratio for which a stable jet flow is acquired from experience.
(8) Width of large flow pipe	It is preferable that the width of the large flow pipe is as large as possible to reduce the flow damper resistance during large flow. Therefore, the width of the large flow pipe is specified to make it as large as practical according to the structure considering the facing angle of the large flow and small flow pipe.
(9) Facing angle of large flow pipe and small flow pipe	The facing angle of the large flow and small flow pipe is specified to balance the angular momentum of each other so that no vortex is formed in the chamber during large flow considering the width of large flow pipe.
(10) Expansion angle of the throat	It is preferable that the flow area from the throat to outlet pipe increases gradually in order to return the kinetic pressure to the static pressure during large flow. However, if the expansion angle is too large, the flow may strip off the pipe and cause an energy loss. Therefore, the expansion angle is specified as [] degrees which is less than [] degrees which prevents flow stripping based on experience.

4.0 CONFIRMATORY TESTING PROGRAM FOR THE ACC

The design requirements and specifications of the ACC for the US-APWR that were discussed in Sections 2 and 3 are the same as that for the APWR. The core power and the size of the reactor vessel are the main parameters used to determine the design requirements and the specifications of the ACC are common to both the APWR and the US-APWR. Therefore, the ACC confirmatory test program previously performed for the APWR is applicable to the US-APWR. This test program was conducted as a joint study among five utilities^{Note} and MHI, from September 1994 to September 1996.

Note: Japan Atomic Power Co., Hokkaido Electric Power Co., Kansai Electric Power Co., Shikoku Electric Power Co., and Kyushu Electric Power Company.

This section of the Topical Report; (1) describes the purposes and objectives of the confirmatory test program; (2) provides a detailed description of the tests and the test results; (3) provides demonstration of the validity and scalability of the test results for the design of the US-APWR; and (4) sets, the quality assurance requirements to re-verify and confirm that the results of the test program are reliable and accurate for use in the design of the US-APWR.

4.1 Purpose of the ACC Scale Testing

Confirmatory tests were conducted to determine whether the expected performance from the operational principles of the ACC could actually be achieved. The following items were tested to verify the principles and characteristics of the flow damper:

(1) Confirmation of the principles of the flow damper:

Tests were conducted to observe the behavior of the flow in the vortex chamber of the flow damper during large flow injection, large/small flow switching, and small flow injection to confirm that their actual behavior was as expected.

(2) Confirmation of the anti-vortex function at the end of large flow injection:

As water level in the accumulator decreases after initiation of accumulator injection, it may be possible to form a vortex at the entrance to the standpipe and the nitrogen gas in the ACC gas space can be sucked into the standpipe when the water level is low. Therefore, an anti-vortex cap was designed for the large flow inlet. The tests were conducted to confirm that the anti-vortex cap prevented the vortex from forming at the standpipe inlet and that gas was not sucked into the standpipe.

(3) Confirmation of the standpipe water level transient during flow switching:

During flow switching from large flow to small flow, the standpipe water level is temporarily decreased by inertial force, and then recovers due to the differential pressure of the water level between the tank and the standpipe. When the standpipe water level decreases to the top of the flow damper, gas can be entrained in the flow damper and injected to the RCS.

However, the ACC was designed so that gas entrainment will be precluded.

A test was conducted to confirm that gas was not entrained into the flow damper by measuring the water level transient during the flow switching.

(4) Confirmation of performance during large flow:

A test was conducted to confirm that the performance of the flow damper during large flow met the design requirement (i.e., resistance coefficient for large flow injection)

(5) Confirmation of performance during small flow:

A test was conducted to confirm that the performance of the flow damper during small flow met the design requirement (i.e., flow switching ratio).

(6) Confirmation of flow switching water level:

It is assumed that the injection flow rate shifts from large flow to small flow when the tank water level decreases to the lower edge of the standpipe anti-vortex cap. However, in the actual tank, the flow switching level may have some variations. Therefore, the actual switching level was confirmed through testing.

(7) Confirmation of the effect of dissolved nitrogen gas:

Since the accumulator is compressed by nitrogen gas, nitrogen gas may dissolve in the water. If the water in the accumulator contains dissolved nitrogen gas, it is assumed that the gas comes out of solution and affects the flow characteristics of the flow damper. Therefore, a test was conducted with nitrogen-rich water to confirm that the effect of nitrogen gas did not significantly effect the ACC performance.

(8) Confirmation that the ACC flow characteristics are represented by dimensionless numbers (cavitation factor and flow rate coefficient):

The throat portion of the ACC is located at the outlet of the vortex chamber in order to form a strong vortex in the vortex chamber during small flow. Therefore, it is assumed that cavitation could occur and affect the flow characteristics during large flow. The cavitation phenomenon can be evaluated by utilizing a cavitation factor. The tests were conducted to confirm that the flow characteristics obtained through the tests were a function of the cavitation factor for large flow and independent of cavitation factor for small flow.

The cavitation factor, σ_v , is defined by the following equations.

$$\sigma_v = \frac{P_D + P_{at} - P_v}{\Delta P} \quad (4-1)$$

where

- P_{at} : Atmospheric pressure
- P_D : Outlet pressure of flow damper [gage]
- P_v : Vapor pressure of the water
- ΔP : Total pressure drop of flow damper

With regard to flow rate coefficient, the definition is described in Section 4.2.3.

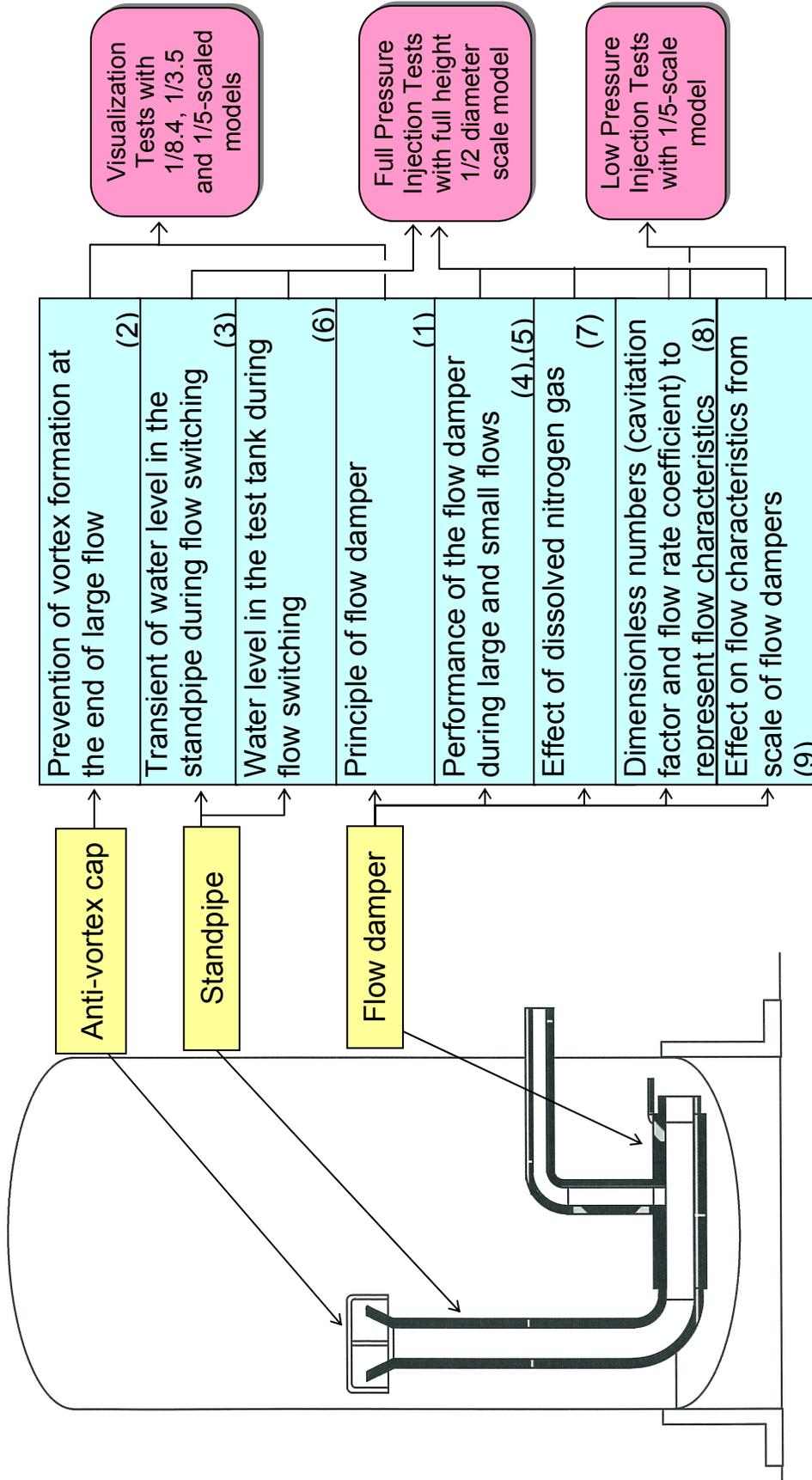
- (9) Confirmation that flow characteristics (cavitation factor and flow rate coefficient) are not significantly impacted by scaling:

To confirm the validity of applying the similarity law to evaluate the actual flow damper by using the scale model test results of the flow damper and to acquire the required data.

These test items are summarized in Fig.4.1-1.

Tests

Items to be confirmed



() shows number of confirmation item from Section 4.1

Fig. 4.1-1 Confirmation Items by Test

4.2 Detailed Description of the Test and Results

4.2.1 1/8.4 Scale Test

1) Objectives

A 1/8.4 scale flow visualization experiment was designed to examine the basis of operation of the ACC and to understand the injection flow characteristics. Items to be confirmed by this test are as follows:

- **Confirmation of operating principles of the flow damper**

Visualize the behavior of flow in the flow damper and the standpipe during large flow injection, large/small flow switching, and small flow injection. Confirm the behavior and stability of the flow in the vortex chamber and flow switching. From this test, it was confirmed that: (1) a vortex was not formed in the vortex chamber during large flow, (2) a vortex was formed and flow rate decreased during small flow, and (3) injection flow rate was sharply switched from large to small flow.

- **Confirmation of behavior of the water level in the standpipe at flow-switching**

Visualize the behavior of the water level in the standpipe at flow-switching and confirm the behavior of the flow.

2) Test Apparatus

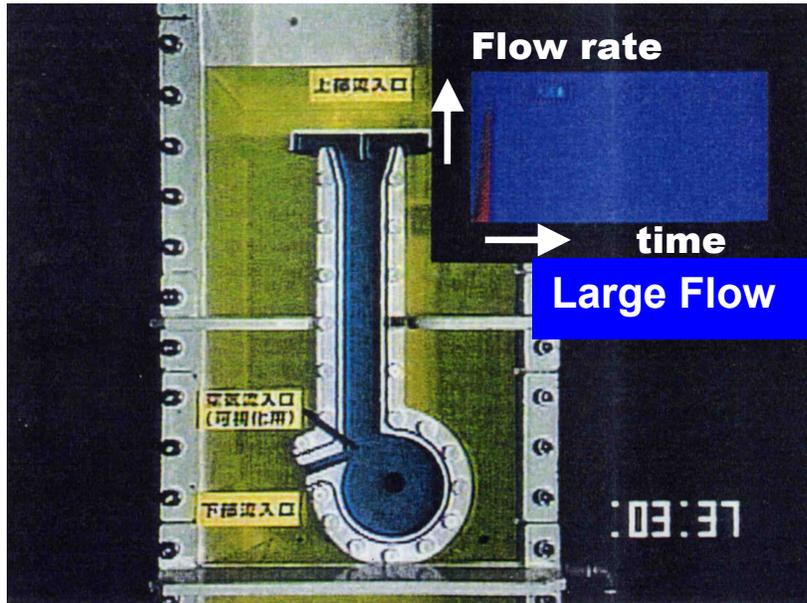
The visualization test of the operating principles of the flow damper was conducted using the test apparatus shown in Fig. 4.2.1-1 and Photo. 4.2.1-1. The test apparatus consisted of an ACC model, exhaust tank, and injection pipe. The scale of the flow damper was 1/8.4 and the vortex chamber is upright. One side of the vortex chamber and the standpipe was integrated into the front of the ACC model which was made of transparent acrylate so that the flow behavior inside of the ACC, the standpipe and the flow damper could be observed. (The shape of each part of the apparatus was simplified while assuring the operating principles of the flow damper was not affected.)



Fig. 4.2.1-1 1/8.4 Scale Test Apparatus

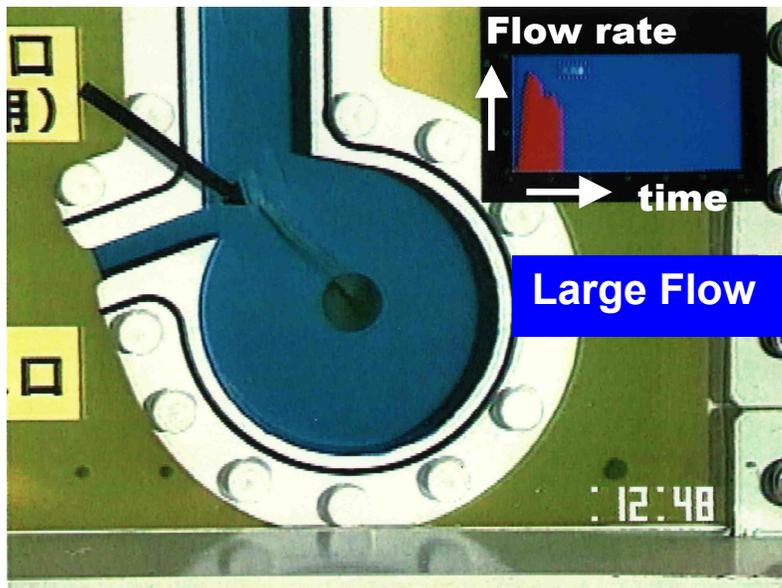


- (1) When the water level in the accumulator is above the upper end of the standpipe, the flow from the standpipe and the small flow inlet collide in the vortex chamber and flow directly to the outlet. A vortex is not formed in the vortex chamber. Therefore, the resistance is small and the large flow rate is available.
- (2) When the water level in the tank is reduced below the upper end of the standpipe, the flow from the standpipe almost stops and only the flow from the small inlet flows into the vortex chamber. A strong vortex is formed. Therefore, the flow resistance is large and the injection flow rate becomes small. No cavitation was observed at the center of the vortex.
- (3) When the water level is close to the flow switching level, it was confirmed that the anti-vortex cap on the standpipe prevents a vortex from being drawn into the standpipe. The lower end of the anti-vortex cap is almost at the same level as the upper end of the standpipe. If the water level in the tank is reduced below the lower end of the anti-vortex cap, the flow from the standpipe almost rapidly comes to a near-stop.
- (4) During the flow switching, the water level in the standpipe is temporarily reduced by inertial force. However the water level recovers quickly, the flow in the standpipe comes to a near-stop, and the water level in the standpipe is maintained. Therefore, gas does not enter into the vortex chamber from the standpipe.



- 3.37 seconds after initiation of the test

Photo. 4.2.1-2 Flow in the Standpipe and the Vortex Chamber during Large Flow



- 12.48 seconds after initiation of the test
- Air injection into the vortex chamber
(This Photo. shows that the vortex is not formed in the vortex chamber.)

Photo. 4.2.1-3 Flow in the Vortex Chamber during Large Flow